

On the Specific Heat of, Heat Flow from, and other Phenomena of, the Working Fluid in the Cylinder of the Internal Combustion Engine.

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The present investigation was undertaken with the object of determining the specific heat of, and heat-flow from, the highly heated products of combustion which constitute the working fluid within the cylinder of an internal combustion engine, by a method which permitted direct observations to be made upon an actual charge taken into the engine in the ordinary operations of its cycle.

The method of experiment is very simple, and the writer believes it to be novel. It consists in subjecting the whole of the highly heated products of the combustion of a gaseous charge to alternate compression and expansion within the engine cylinder while cooling proceeds, and observing by the indicator the successive pressure and temperature-falls from revolution to revolution, together with the temperature and pressure rise and fall due to alternate compression and expansion. The engine is set to run at any given speed, and at the desired moment after the charge of gas and air has been drawn in, compressed, and ignited, the exhaust valve and charge inlet valves are prevented from opening, so that when the piston reaches the termination of its power stroke, the exhaust gases are retained within the cylinder, and the piston compresses them to the minimum volume, expands them again to the maximum volume, and so compresses and expands during the desired number of strokes.

Fig. 1 is an indicator diagram so obtained, and it will be noted that, in addition to the usual power diagram, a series of lines are traced which show the gradual cooling of the hot contents of the cylinder through the enclosing walls. The mode of dealing with these observations will be apparent from the following considerations :—

If a gas be compressed without gain or loss of heat from volume V_0 to V_1 , and temperature rises from T_0 to T_1 , so that the work done upon the gas is W , then the mean specific heat C_v of the gas per unit volume at 0° and 760 mm. at constant volume between the temperatures is

$$C_v = \frac{W}{\psi_0 (T_1 - T_0)},$$

where ψ_0 is a constant depending on the quantity of gas in the cylinder.

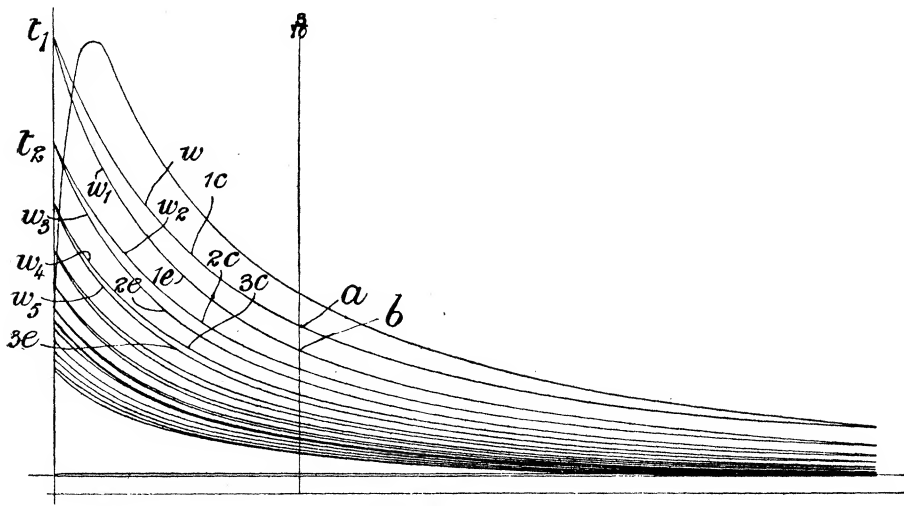


FIG. 1.

It will be found more convenient to consider the specific heat per cylinder full of gas; if this specific heat value be S ,

$$S = C_v \psi_0 = \frac{W}{T_1 - T_0}. \quad (1)$$

If different gases could be sufficiently compressed adiabatically, and the work of compression accurately measured, the value of S could be obtained for any given temperature range. In actual apparatus, heat exchanges of course take place between the gas and its enclosing walls, so that this method cannot be experimentally applied without means of determining the law of heat flow to and from the gas.

Assume, however, that in the case of an expanding gas the temperature-fall due to heat-flow through the walls is known, and its value for a given case is θ_m , while the temperature-fall during the given expansion is $t_1 - t_{01}$; if the total work done by the expansion is W_m , then the mean specific heat S for the temperature range t_1 to t_{01} is

$$S = \frac{W_m}{(t_1 - t_{01}) - \theta_m}, \quad (2)$$

That is, by deducting the temperature-fall due to heat-flow from the total temperature-fall, as shown by the expanding line, there is at once obtained the temperature-fall which is caused by the gas doing work W_m upon the piston. It is therefore only necessary to determine the temperature-fall due to heat loss on any given expansion line to be enabled to at once calculate the mean specific heat of the gas for the temperature limits.

The law of heat-loss cannot be ascertained by any consideration of

compression or expansion curves separately, unless the specific heat values of the gas be known.

By subjecting a gas, however, to alternate compression and expansion, at a relatively rapid rate, the law of heat-flow and its absolute value can be ascertained, and hence the mean specific heat determined, whether it be constant or variable throughout the temperature range.

Assume a gas at a higher temperature than its enclosing walls to be alternately compressed from volume V_0 to V_1 , and expanding from V_1 to V_0 , as illustrated in fig. 2. The successive pressures at the volume V_0 are indicated at the points A, C, E, G, and I, while those at volume V_1 are B, D, F, H and J. The gas is thus compressed from A to B; C to D; E to F; G to H; and I to J; and it is expanded from B to C; D to E; F to G; and H to I. Assume that the gas is cooling but remains above the temperature of the walls during these compressions and expansions.

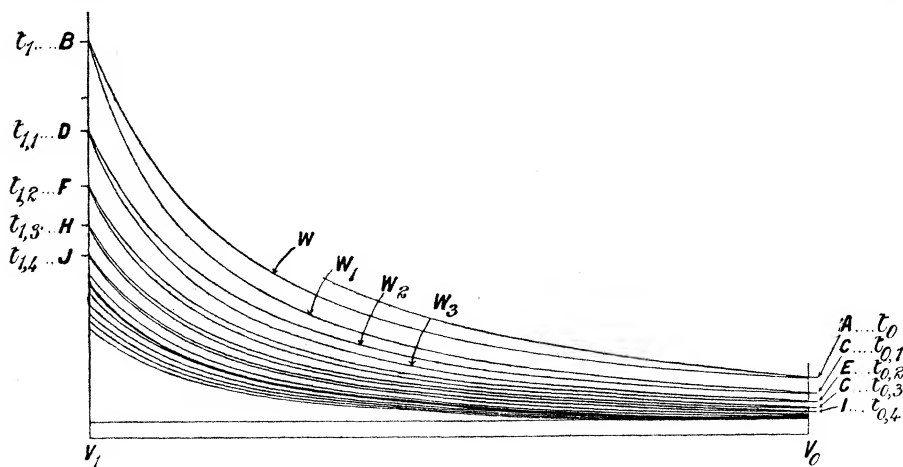


FIG. 2.

During the first compression, work is done upon the gas equal to W ; during the first expansion, B to C, work is done by the gas upon the piston equal to W_1 , and the pressure has fallen from the point A to the point C, that is, the gas has been compressed from the volume V_0 to V_1 , and expanded back again to the same volume, while heat is being lost to the sides of the cylinder; work also has been done upon the gas, and has passed away as heat, because W is greater than W_1 . If the absolute temperatures at A, C, E, G, and I be $t_0, t_{01}, t_{02}, t_{03},$ and t_{04} , then the total or true temperature-fall due to heat-loss to the walls in the double operation is

$$g_0 = (t_0 - t_{01}) + \frac{W - W_1}{S}, \quad (3)$$

S being mean specific heat at constant volume in work units for the temperature range between A and C.

For the successive double operations between C, E, G and I, the true temperature-falls due to heat-loss through the walls are obtained in the same way. Taking temperature-falls between these points as g_{01} , g_{02} , g_{03} , etc.,

$$g_{01} = (t_{01} - t_{02}) + \frac{W_2 - W_3}{S_1}, \quad \text{etc.}, \quad (4)$$

that is, the true temperature-falls g_0 , g_{01} , g_{02} , g_{03} , etc., are greater than the apparent falls $(t_0 - t_{01})$, $(t_{01} - t_{02})$, etc., by temperature-fall equivalents of the respective work-areas $W - W_1$; $W_2 - W_3$; etc.

During the first expansion from B to C work is done by the gas upon the piston equal to W_1 , and the second compression, C to D, does work upon the gas W_2 , and so on. Meantime the pressure has fallen from the point B to the point D; that is, the gas has been expanded from volume V_1 to V_0 , and compressed back again from V_0 to V_1 , while heat is being lost to the enclosing walls. Work, however, in this case has been done by the gas upon the piston, because W_1 is greater than W_2 . At the minimum volume V_1 the successive points B, D, F, H and J indicate temperature-falls due not only to heat-loss through the walls, but also due to some work done upon the piston. If the absolute temperatures at B, D, F, H and J be taken as t_1 , t_{11} , t_{12} , t_{13} , t_{14} , then the total or true temperature-falls due to heat-loss to the walls in the double operation of expansion and compression are

$$g_1 = (t_1 - t_{11}) - \frac{W_1 - W_2}{S'}, \quad (5)$$

S' being the mean specific heat at constant volume for the temperature range between B and D.

For the successive double operations between D, F, H and J, the temperature-falls due to heat-loss through the walls are obtained in the same way. Taking temperature-falls between those points as g_{11} , g_{12} , g_{13} , etc.,

$$g_{11} = (t_{11} - t_{12}) - \frac{W_3 - W_4}{S'_1}, \quad \text{etc.}, \quad (6)$$

that is, the true temperature-falls g_1 , g_{11} , etc., are less than the apparent falls $(t_1 - t_{11})$, $(t_{11} - t_{12})$, etc., by the temperature equivalents of the respective work-areas $(W_1 - W_2)$, $(W_3 - W_4)$, etc. To calculate the specific heat from the expansion lines BC, DE, FG and HI, it is necessary to know the work-areas W_1 , W_3 , W_5 and W_7 , as also the temperature-falls, θ_n , due to heat flow through the enclosing walls. All these values are given by direct readings from the diagrams, except the latter, θ_n , and to determine this it is necessary to convert the differences between the work-areas concerned into their

temperature-fall equivalents. For this purpose the values S, S_1, S', S'_1 , are required; that is, the specific heats must be known before an accurate cooling curve can be prepared. This can be readily done with sufficient accuracy with two approximations. For a first approximation assume that $(t_1 - t_{11}), (t_{11} - t_{12})$, etc., correctly represent the temperature-falls due to heat-flow through the walls; then construct a curve showing temperature-drop per revolution, shown in black line at fig. 3, which is taken from Card No. 22.*

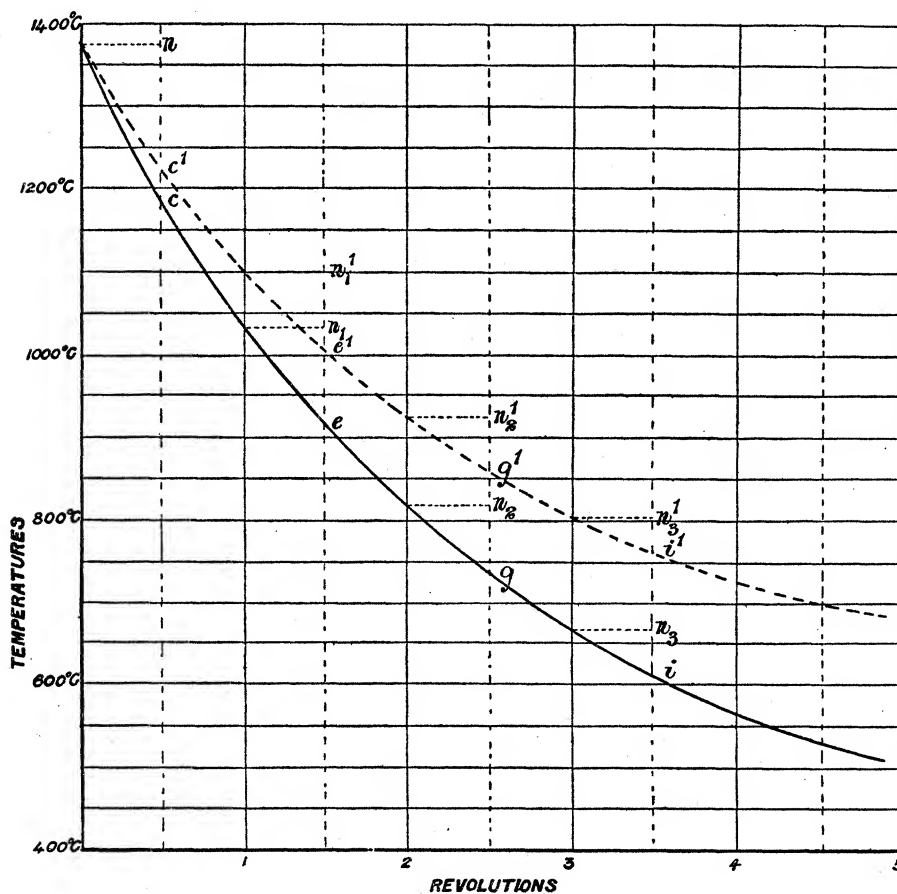


FIG. 3.

From this curve it will be seen that the temperature-drop assumed entirely due to heat-flow in one expansion stroke BC is equal to the ordinate cn ; let

* The original enlarged indicator diagram cards are preserved for reference at the Royal Society.

this be g_n , then

$$S_n = \frac{W_1}{(t_1 - t_{01}) - g_n}. \quad (7)$$

Values similar to S_n are calculated from the losses on DE, FG, etc., then these values are used to calculate g_n, g_{n1}, g_{n2} , etc., the temperature-fall equivalents of the areas $(W_1 - W_2)$; $(W_3 - W_4)$; $(W_5 - W_6)$; etc.

$$g_n = \frac{W_1 - W_2}{S_n}, \quad g_{n1} = \frac{W_3 - W_4}{S_n}, \quad \text{etc.}$$

If then g_n, g_{n1}, g_{n2} , etc., be deducted from $(t_1 - t_{11})$, $(t_{11} - t_{12})$ and $(t_{12} - t_{13})$, etc., we get values $(t_1 - t_{11}) - g_n$, $(t_{11} - t_{12}) - g_{n1}$, etc., which give successive temperature-falls per revolution. These are used to construct a second temperature-fall curve. This curve is shown in fig. 3 in dotted lines. By using the new values of the temperature-falls equal to the ordinates $c'n, e'n'_1, g'n'_2$, etc., another value of the specific heat is obtained for each expansion line, and a third temperature-fall curve is plotted. This curve, however, lies so close to the dotted curve that it is indistinguishable; and if the dotted curve be used the values so obtained of g_n, g_{n1}, g_{n2} , etc., are accurate within the error of experiment. By applying the same method to the points A, C, E, G and I, adding the temperature-fall equivalent of $(W - W_1)$; $(W_2 - W_3)$; etc., a temperature-fall curve is obtained calculated from the maximum volume, and such a curve is shown at fig. 4 in dotted lines. The specific heats on the different expansion lines are then obtained by (2)

$$S = \frac{W_1}{(t_1 - t_{01}) - g_1}, \quad \text{etc.}$$

It is found, however, that calculations made from the diagrams in this manner are liable to considerable disturbance due to possible indicator errors so small as 0.1 mm.

It was therefore considered desirable to make the specific heat calculations from measurements relating to the upper part of the diagrams, where the temperature differences to be measured are at a maximum.

In order to determine the law of heat-loss at the upper ends of the diagram, it is necessary to investigate the curve more closely.

If the true temperature-falls due to cooling on the double stroke be plotted with the mean temperatures of the working fluid during the double stroke, and the lines corresponding with the mean temperatures of the expansion stroke be drawn, cutting the curve so produced, it is found that the temperature-falls given by this curve at the mean temperatures of the expansion lines—divided by two to give the correct value for a single stroke—are the same as those found by the method above described from the dotted curve, fig. 3.

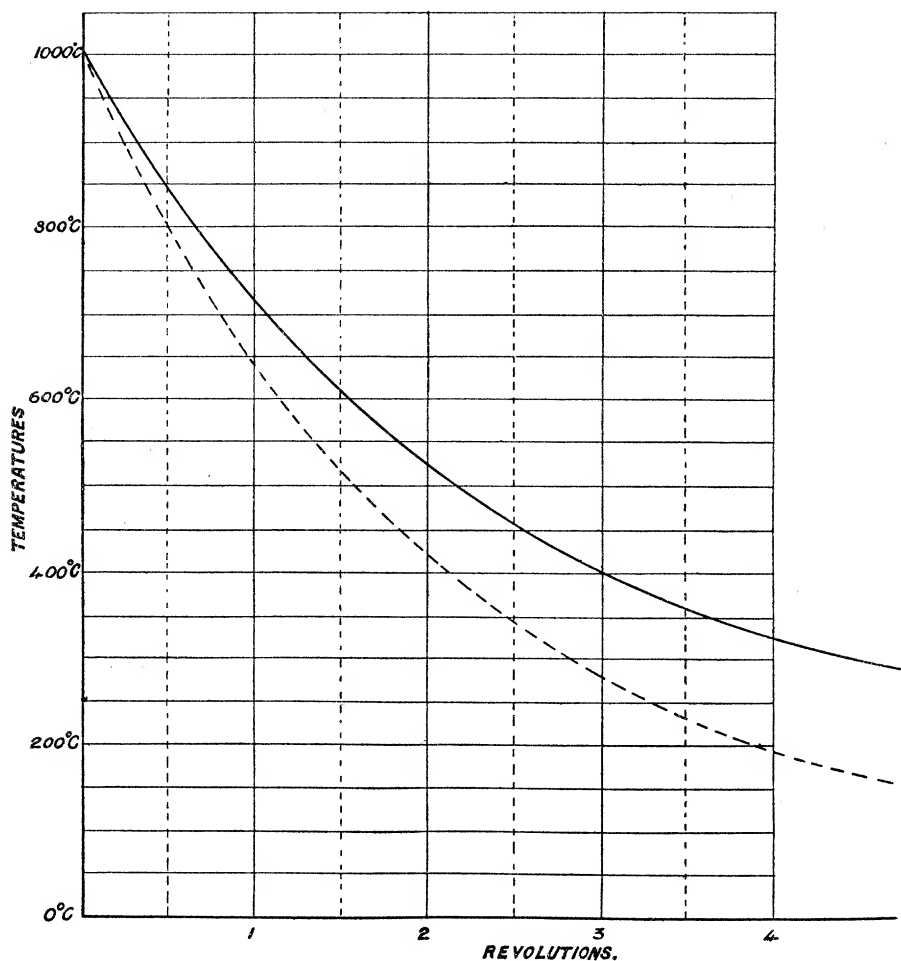


FIG. 4.

Fig. 5 shows such a curve; it has been obtained by measurement of mean temperatures on the successive pairs of compression and expansion lines, and by taking the values of temperature-fall for the double stroke from the dotted curve, fig. 3.

On fig. 5 the full vertical lines cutting the curve are drawn through points representing mean temperatures respectively on expansion and compression lines BC and CD, DE and EF, FG and GH, and HI and IJ. The vertical dotted lines refer to mean temperatures or expansion lines BC, DE, FG and HI only. The temperature-falls shown by the ordinates in full lines are taken from the dotted curve, fig. 3.

Numerous curves of this kind have been calculated, and prove that the

temperature-fall may without appreciable error be taken from the mean temperature curve in this way. This fact is applied to the determination of temperature-falls at the high-pressure part of the stroke as follows:— Referring to fig. 1, the vertical line marked $3/10$ cuts the expansion and compression lines of the diagram at three-tenths of the engine stroke. This is the part which is to be investigated to determine specific heat. To distinguish the partial from the complete lines, the compression lines on fig. 1 are marked successively $1c$, $2c$, $3c$, etc., and the expansion lines $1e$, $2e$, $3e$, etc.

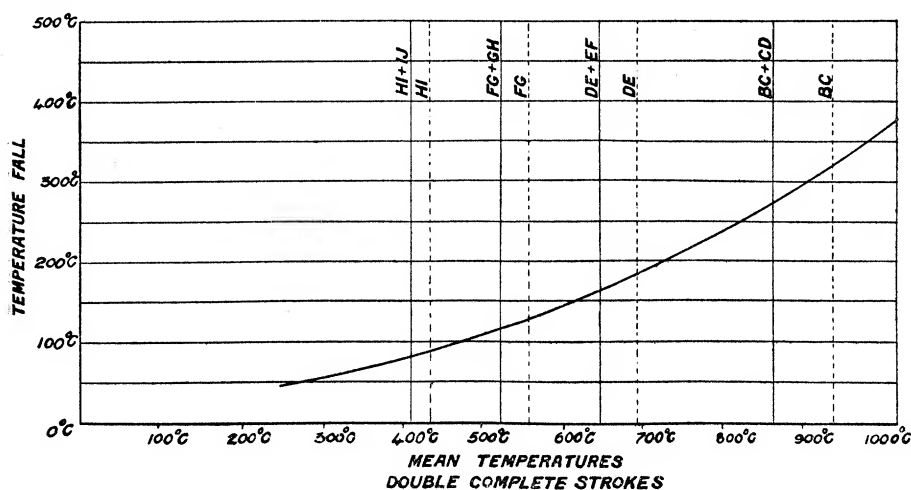


FIG. 5.

Work is done upon the gas equal to w on the first compression line $1c$, and done by the gas on the piston by the first expansion line $1e$, the work being w_1 . The heat lost during the partial compression and expansion is thus measured by the temperature-fall between a and b plus the temperature-fall equivalent of the area $w - w_1$. By using the specific heat value already calculated for the complete expansion line, the value of the total temperature-fall g equivalent to the heat lost is obtained. The total temperature-fall has now to be divided between the compression and expansion lines. For this purpose the mean temperatures are calculated for $1c$ and $1e$, and a mean temperature-fall curve drawn for the upper three-tenths stroke (see fig. 6).

On fig. 6 the full vertical lines cutting the curves are drawn through the mean temperatures respectively of the partial compression and expansion lines $1c$ $1e$, $2c$ $2e$, $3c$ $3e$, and $4c$ $4e$, and the dotted lines $1e$, $2e$, $3e$, and $4e$. A value, g_{1e} , for the temperature-fall on the expansion line $1e$ is taken from

the curve, fig. 6. The mean specific heat on the expansion line 1e is thus

$$S_{1e} = \frac{W_1}{(t_1 - t_b) - g_{1e}},$$

between the temperature limits t_1 and t_b . The other expansion lines are calculated in the same manner.

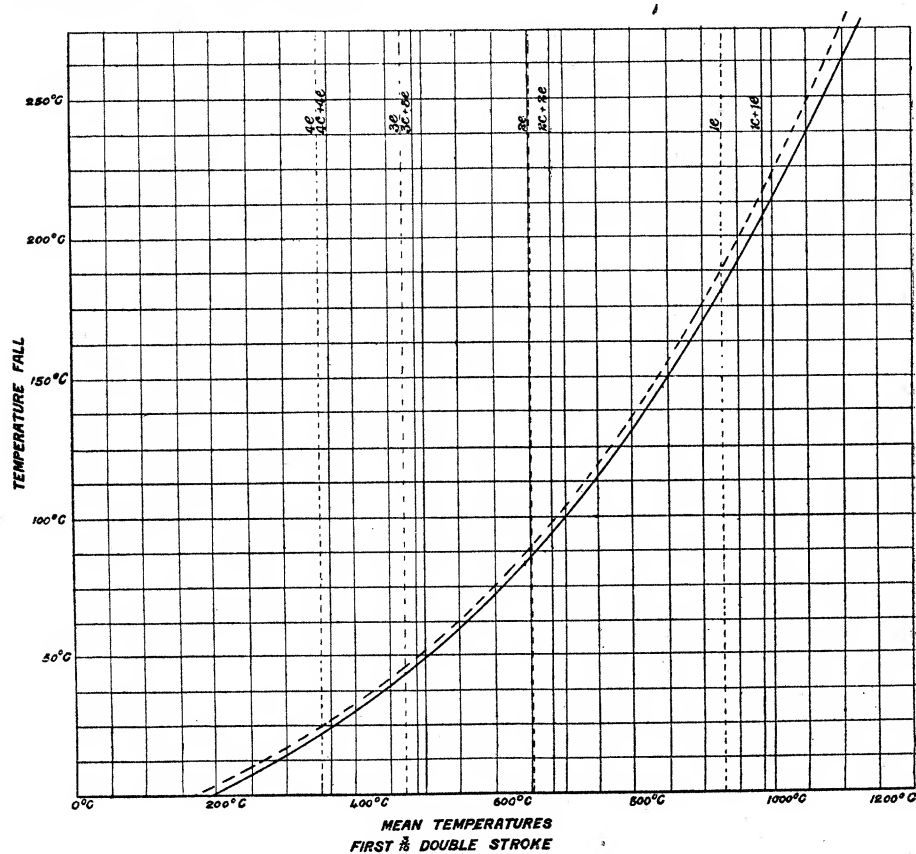


FIG. 6.

It was found that the specific-heat values obtained as above from the upper three-tenths diagram were lower than those obtained for the whole stroke. New temperature-fall curves were, therefore, drawn for each diagram, taking the average specific-heat value found as above described, on the upper three-tenths stroke. One of these curves is shown in dotted lines in the diagram 6.

The final specific-heat calculation was made, using these temperature-fall curves in a similar manner to that described above. It was found that the temperature-fall curves obtained by using the specific heat finally obtained

do not differ appreciably from the curves obtained when the average specific-heat value on the upper three-tenths stroke is used. It was, therefore, unnecessary to make a further calculation.

So much for the method of examination and calculation adopted. In what follows, the last described method of obtaining specific heat has been followed.

Engine and other Apparatus for Experiments.—The engine used for the experiments was of the well-known four-cycle type, 14 inches diameter cylinder and 22 inches stroke, designed for a full load of 60 brake horsepower at 160 revolutions per minute. It was constructed by the National Gas Engine Company, Limited, and was used by the Thermodynamic Standards Committee of the Institution of Civil Engineers, in conjunction with the present writer, for determination of data required for an ideal standard of comparison. It was carefully measured and calibrated by the Committee, the relevant matters being as follows:—

	cub. ins.
Volume swept by piston-stroke	3390
Total volume.....	4164
Compression space	774
Compression per cent. of total volume ...	18·59

Fig. 7 shows a vertical longitudinal section and part horizontal section. The indicator used was of the Casertelli Richards type. It was carefully measured, and the springs calibrated, by the writer.

The coal-gas drawn into the cylinder was measured by a meter which had been tested by the Committee, and the air supplied was also measured by anemometer, also calibrated by the Committee. During the experiments, observations were made of temperatures of gas, air, and water flowing into and out of the engine water-jacket. Analyses of the coal-gas used were made, and the heat of its combustion was determined by the Junker calorimeter. No leakage could be detected past either piston or valves during the experiments.

Apparent Specific-Heat Values.—To determine the specific-heat values, the engine was run without load, and the governor adjusted to keep the speed at about 120 revolutions per minute. The total revolutions were determined by counter; the total number of explosions were also so determined. The water-jacket was kept cold by passing water through it at a sufficient rate. Gas consumption was taken, and barometer and thermometers read. The rate of engine revolutions was also taken by tachometer.

To make an observation the indicator cock was opened and a trigger operated,

after a gas charge had been taken in, to liberate the springs, pressing on the exhaust and inlet valve cam rollers. The springs displaced the rollers along their pins, placing them beyond the action of the cams. Consequently, the exhaust and inlet valves remained closed, so that although the electric spark produced the usual power-stroke explosion, the products of combustion produced were entirely retained in the cylinder and alternately compressed and expanded behind the piston, the engine being driven by the energy of rotation of the fly-wheel.

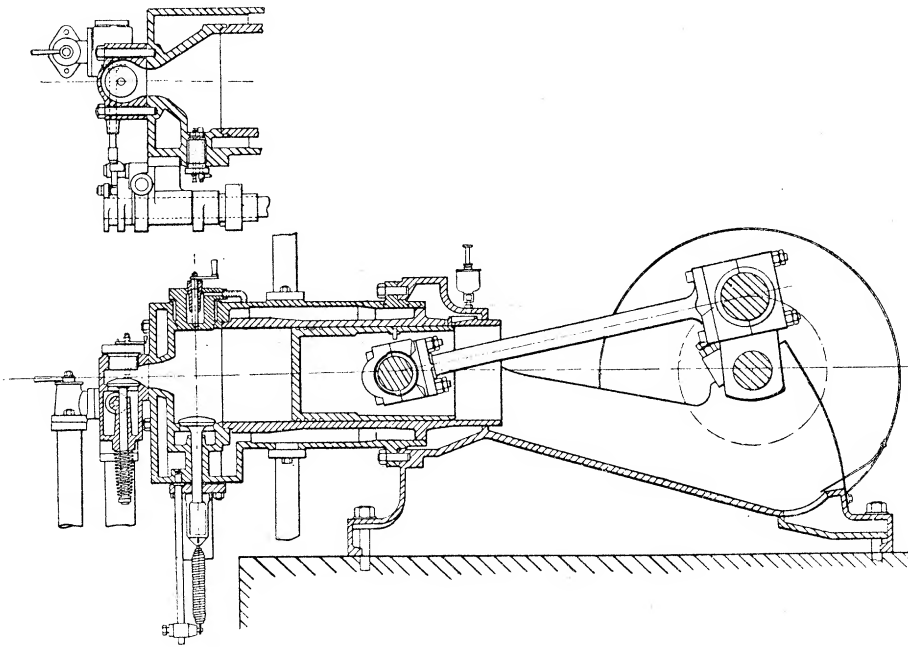


FIG. 7.

The indicator pencil was lightly held against the card during a number of revolutions and traced a series of gradually falling lines. The tachometer was observed and readings made at the moment of explosion, and at the moment of last contact with the card. In this way the actual time of each double operation was accurately known. During the first five revolutions after explosion the speed dropped from about 120 revolutions to 116 revolutions, so that the variation was only from 3 per cent. to 4 per cent. This variation, however, has been allowed for in preparing the cooling curves. Indicator diagrams were also taken with a light spring to determine the pressure of the charge within the cylinder on the completion of the charging stroke. It was found that the cylinder was entirely filled at this low

speed, so that the pressure within was the same as that of the external atmosphere.

Thirty indicator cards were taken at this speed for examination, and the proportions of the gas to air were varied within narrow limits to discover whether a slight change in composition changed the specific-heat values materially. The values of specific heat given are the mean values obtained from 21 cards, in which the mixture was of nearly the same proportions.

To facilitate measurement of the faint lines upon the cards, enlarged photographs were taken, doubling the scale. All measurements required for the calculations were made from these photographs. Enlargements Nos. 1 to 21 accompanying this paper (see footnote, p. 504), are those from which the apparent specific-heat values are deduced. In calculating from the diagrams, the following assumptions have been made:—

- (1) That $PV/T = \text{a constant}$ for all temperatures and pressures of the experiments.
- (2) That $PV = \text{a constant}$ for isothermal compression or expansion for all the experiments.
- (3) That no chemical contraction or expansion has taken place due to combustion.
- (4) That combustion is complete after seven-tenths of the first compression stroke.

Five expansion lines were examined on each card, and the various values described were calculated from carefully-made measurements.

The curve shown at fig. 8 was obtained from Cards 1 to 21 in this manner, so far as concerns the observed points *a*, *b*, *c*, *d*, *e*, each of which points is the average value of the numbers calculated from 21 cards. These points carry the apparent instantaneous specific-heat values up to 920° C. The point *f* was calculated in a similar manner from the upper one-tenth of the diagram, and the point *g* was obtained by similar processes from the explosion expansion line between one-tenth and three-tenths of the forward stroke. The observed points represent the average specific heats for the ranges of temperature of successive expansion lines, and the curve shown is so drawn that the average specific heats given by the curve over the same temperature ranges are equal to the observed values. The value at 0° C. is obtained by extrapolation, assuming all products to remain gaseous. The mean values from 0°—200° calculated from the usually accepted numbers are given, and it appears to be 20·25 where the curve shows 20·9. The specific heats are given in foot-pounds per cubic foot of working fluid

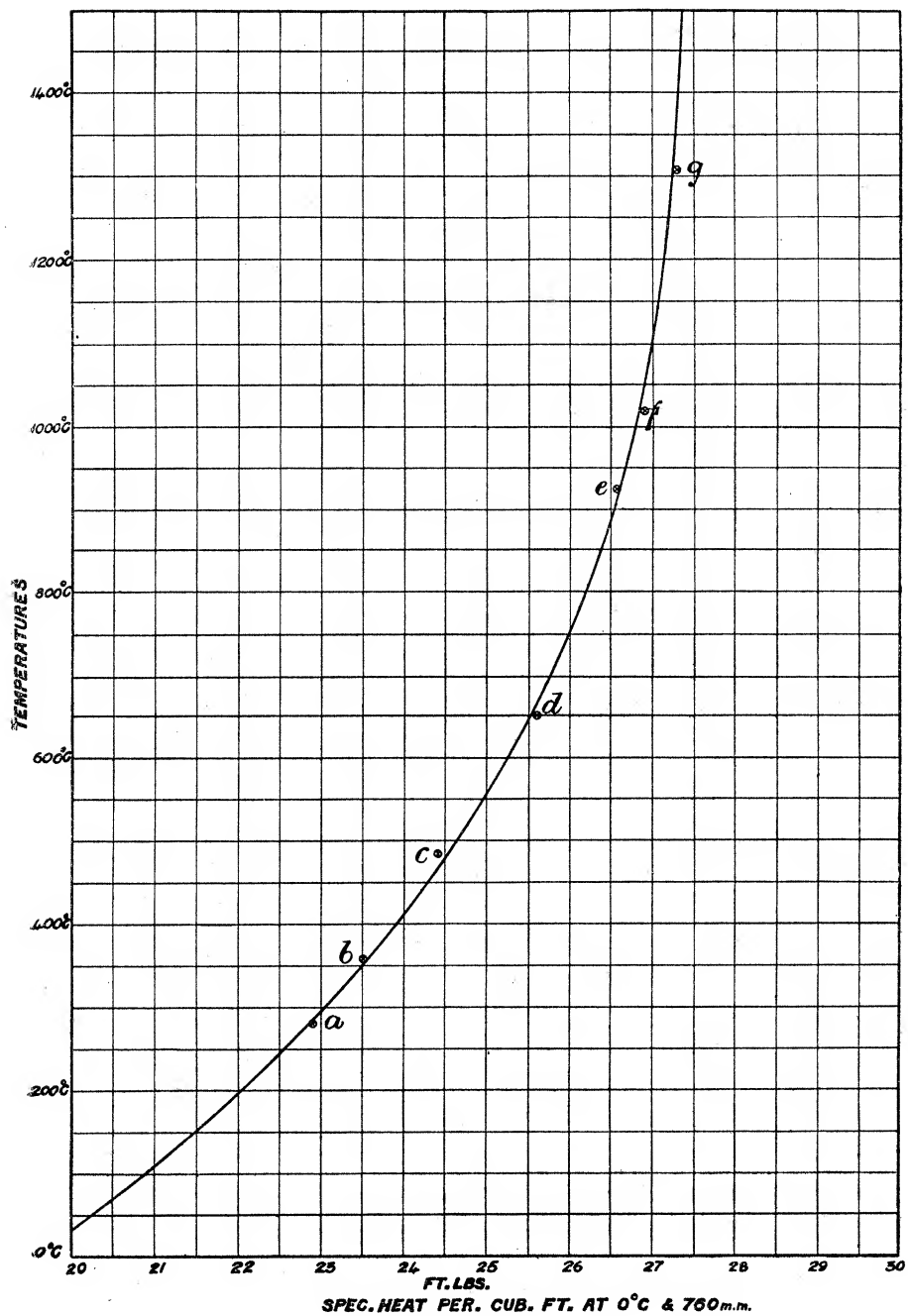


FIG. 8.

reduced to standard temperature and pressure 0°C. , and 760 mm. mercury. The highest temperature measured for the purpose of this curve was 1450°C. , and the lowest 250°C.

The mean composition by volume of the working fluid calculated from analysis of the coal-gas used at the works was

	Vols.
Steam (assumed gaseous) ...	11.9
Carbon dioxide	5.2
Oxygen	7.9
Nitrogen.....	75.0
	100.0

The mixture, however, was varied slightly between the extreme compositions, viz.:—

	Vols.	and	Vols.
Steam (assumed gaseous).....	11.2		12.7
Carbonic anhydride	4.8	„	5.5
Oxygen	8.7	„	7.0
Nitrogen	75.3	„	74.8
	100.0		100.0

These two extreme compositions correspond respectively to explosive mixtures containing before combustion 1 volume gas to 9.8 volumes air, and 1 volume gas to 8.5 volumes air.

The composition by volume of the coal-gas used was (average age of four analyses):—

Hydrogen	43.0
Marsh gas	33.2
Unsaturated hydrocarbons	4.3
Carbon monoxide	6.7
Nitrogen.....	10.2
Oxygen	0.3
Carbon dioxide	2.3
	100.0

Table I shows the apparent instantaneous specific heats at different temperatures taken from the curve; and Table II shows mean apparent specific heats for temperature ranges from 0°C. up to 1500°C.

From these numbers it is evident that the apparent specific heat of the

working fluid consisting of products of combustion in the cylinder of the internal combustion engine increases considerably with temperature, so that at 1000° C. the value is 28 per cent. greater than it is at 100° C., while at 1500° C. the increase amounts to 31 per cent. The mean apparent specific heat between 0° and 1000° C. is 24.1 foot-pounds per cubic foot, or 15 per cent. greater than at 100° C., while at 1500° C. the increase amounts to over 20 per cent.

Table I from Fig. 8.—Table of Apparent Specific Heats (Instantaneous) in foot-pounds per cubic foot of Working Fluid at 0° C. and 760 mm.

Temperature.	Specific heat at constant volume.	Temperature.	Specific heat at constant volume.
° C.	ft.-lbs.	° C.	ft.-lbs.
0	19.6	800	26.2
100	20.9	900	26.6
200	22.0	1000	26.8
300	23.0	1100	27.0
400	23.9	1200	27.2
500	24.8	1300	27.3
600	25.2	1400	27.35
700	25.7	1500	27.45

Table II from Fig. 8.—Table of Mean Apparent Specific Heats in foot-pounds per cubic foot of Working Fluid at 0° C. and 760 mm.

Temperature.	Specific heat at constant volume.	Temperature.	Specific heat at constant volume.
° C.	ft.-lbs.	° C.	ft.-lbs.
0—100	20.3	0—900	23.9
0—200	20.9	0—1000	24.1
0—300	21.4	0—1100	24.4
0—400	21.9	0—1200	24.6
0—500	22.4	0—1300	24.8
0—600	22.8	0—1400	25.0
0—700	23.2	0—1500	25.2
0—800	23.6		

Inspection of the curve at once shows that while apparent specific heat increases more rapidly at first, it tends to a limit at the upper temperatures, so that from 1200° C. to 1500° C. the increase is less than half that from 900° C. to 1200° C. The appearance of the curve would suggest a limit for the apparent specific-heat value after no great further increase in temperature.

Is this a real increase of specific heat? If combustion be completed, then there appears to be no other explanation.

Consider, however, the points of difference which arise between a real change of specific heat with changing temperature and an apparent change caused by continued combustion. If the continued combustion be due to dissociation, then it would be impossible to differentiate by any experiments of this kind; but if it be combustion continuing at a given time rate, then discrimination is possible. With a real specific-heat change it is obvious that values calculated from any expansion line will show a fall along that line depending on temperature-fall only. No increase of specific heat could occur on the falling temperature expansion line. This is also true for change due to dissociation. If, however, combustion be continuing, then the apparent specific heat may vary from point to point of the line depending on the relations between the instantaneous values of the rates of heat addition to the working fluid and work performed by it, on the piston.

If the rate of heat addition be less than that of work performed, then the temperature will fall; but if the work rate diminishes more rapidly than the combustion rate, then at a certain point of the expansion the rates may become equal and then the expansion line may become isothermal, and it is even conceivable that temperature might rise. In such a case specific-heat values calculated from point to point of the supposed expansion line would show an increase with falling temperature, and at the isothermal point would become infinitely great. If combustion continues at a rate which becomes relatively greater than the work rate, it is evident then that specific-heat values will increase all along the expansion line as pressure and temperature falls. It has been already stated that this is found to be the case, but numerous calculations have been made from many diagrams which always show this interesting effect. To illustrate this point calculations have been made from Card No. 5, expansion line BC for: first three-tenths of stroke; first half of stroke; second half of stroke; and the whole stroke, as follows:—

Apparent Specific Heat.

First three-tenths of stroke...	26·3	ft.-lbs.	per cubic foot	at 0° C. and 760 mm.
First half of stroke.....	27·3	"	"	"
Second half of stroke	34·3	"	"	"
Whole stroke	28·4	"	"	"

Other cards show greater differences between the first three-tenths and the later parts of the stroke, some as much as 50 per cent. increase. It is true

that difficulties of reading and errors of indicator affect the lower ends of the diagram more seriously than the upper, and some allowance must be made for this; but notwithstanding this, the difference between the early parts of the stroke are so marked that it appears very improbable that they can be accounted for by any such errors. Combustion appears to be proceeding.

Other indications are given by varying the rate of revolution of the engine. If specific heat varies only with temperature, then obviously change in engine speed cannot alter specific-heat values. To test this matter four cards were taken at 160 revolutions, and four at 120 revolutions per minute, and calculations were made on expansion line BC for whole stroke, first half stroke and first three-tenths stroke. Results were obtained as follows:—

Apparent Specific Heat.

	160 revs.	120 revs.
Whole stroke	34.4 ft.-lbs.	31.0 ft.-lbs.
First half stroke	29.5 „	28.3 „
First three-tenths stroke ...	27.2 „	26.6 „

This experiment clearly indicates an increase of apparent specific heat with increasing speed as well as increased apparent value with falling pressure. The effect of increasing speed to some extent introduces opposing changes; higher speed means less combustion completed when expansion on the line BC begins, but it also means performance of work on the piston at a greater rate, so that the new factors cancel each other out to some extent.

Still another indication is given by varying the temperature of the water-jacket of the engine, keeping the speed of the engine constant. The experiments were made with the engine running at 120 revs. per minute with the water-jacket cold, 13° C., and hot, 66° C.

Three expansion lines were calculated for the first three-tenths stroke. For cold, Cards 1 to 21 were taken; the values given are mean values of the 21 cards. For the hot experiments eight cards were taken; the values given are means of eight. Results were obtained as follows:—

Apparent Specific Heat.

	Water-jacket, 13° C.	Water-jacket, 66° C.
1e	26.6 ft.-lbs.	23.9 ft.-lbs.
2e	25.2 „	22.6 „
3e	23.9 „	21.9 „

Obviously apparent specific heat is less with the hot water-jacket. This could not affect the matter if the only change with temperature is in specific

heat. The cause of the change may be due to the rise of the mean temperature of the chemical reaction which permits chemical action to be less affected by cooling walls which tend to remove a portion of the contents from the sphere of effective reaction by undue cooling. That is, combustion proceeds more quickly in a hot vessel than a cold one. This would produce the effect of lowered specific-heat value by leaving less heat to be evolved when expansion line BC commenced.

The experiments appear, therefore, to prove that some combustion is proceeding. The nature of the apparent specific heat also changes, as the rate of apparent change is much greater at the lower temperatures, taking the same portion of the stroke.

Experiments made by the Thermodynamic Standards Committee of the Institution of Civil Engineers in conjunction with the present writer appear to support the contrary conclusion, because in this same engine a balance-sheet was determined as follows for 100 heat-units given to the engine.

Indicated work	35.00
*Heat-loss to water-jacket and radiation.....	28.00
*Heat passing away with exhaust determined by calorimeter	38.5
	101.5

This appears to account for the whole of the heat at the conclusion of the return or exhaust stroke. The writer considers, however, that the method used to determine radiation and the exhaust calorimeter might introduce an error of 5 per cent. and possibly more. It is obvious that further experiment is required to settle the question.

Heat-Flow Values.—Curves for temperature-fall values were prepared from the 21 cards used for the determination of apparent specific heat, each curve arranged as described to show temperature-fall in terms of mean temperature of the various expansion and compression lines studied. For convenience of calculation the temperature-fall values were expressed in isothermal units. The method of isothermal units consisted in referring all temperatures to an isothermal line calculated for the particular proportions of the cylinder and compression space. The corrections for temperature-fall were applied to the expansion lines of the same card. As the correct estimation of temperature-fall is important, and the accuracy of the specific-heat values depends upon

* It is known that part of the heat which should appear in the exhaust calorimeter passes into the water-jacket, so that the jacket loss value is too high, while the exhaust loss is too low.

its knowledge, it has been thought desirable to study more closely the mode of heat-loss in the cylinder, and some features which call for explanation.

Fig. 9 has been prepared with this object. Four curves are shown. The curves *a*, *b*, represent the heat-losses incurred in complete revolutions, that is, in complete double strokes. Here the surface exposed and covered alternately is that due to the whole sweep of the piston. The curves *a'*, *b'*, represent losses incurred at the upper three-tenths of the card (see fig. 1) while the piston moves from three-tenths stroke to the end, compressing into the clearance space, and then moves out again to the point of three-tenths of the outward stroke. The ordinates give heat-loss in foot-pounds per second, and the abscissæ mean temperatures per double stroke or double three-tenths stroke.

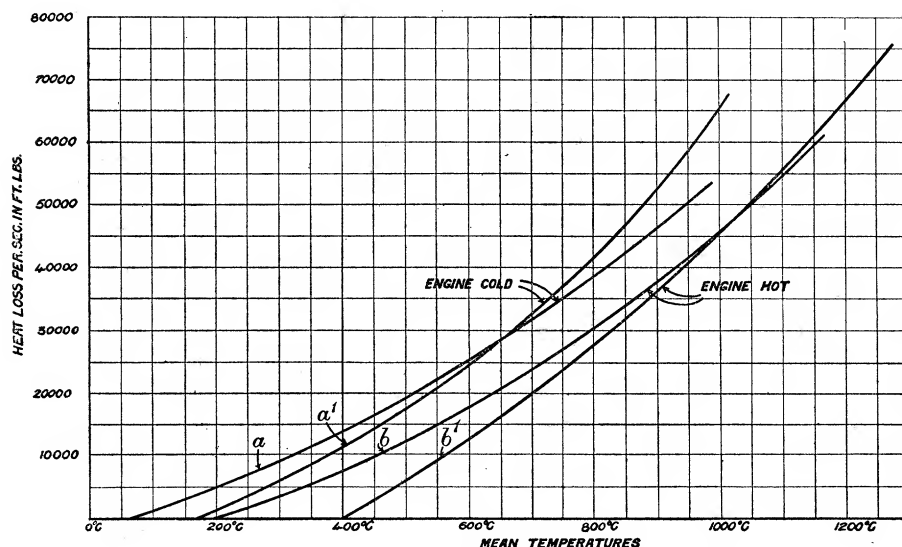


FIG. 9.

Curves *a* and *a'* are calculated from Cards 2, 3 and 5, taken while the engine was running without load at 120 revolutions per minute with the jacket water kept at a mean temperature of 13° C. Curves *b* and *b'* are calculated from Cards Nos. 22, 23 and 24, taken while the engine was running at about 160 revolutions per minute with a load of 50 B.H.P., and the jacket water at 80° C. Accordingly the curves are marked as engine cold and engine hot.

The heat-loss values given are calculated from temperature-fall curves, assuming the apparent specific heats given at fig. 8 and at Tables I and II to be real specific heats; but for the amounts of continued combustion believed

to be present it appears probable that the heat-flow values calculated are also sufficiently close approximations within the errors of experiment.

Taking curve *a*, it appears that the heat-loss is not proportional to temperature difference, but increases more rapidly as temperature rises. Further, the curve, when prolonged to the zero line representing no loss of heat, cuts that line at the temperature 65° C. This appears to show that during complete engine strokes, cooling ceases at that temperature, so that the mean temperature of the inner surface of the enclosing walls must be about 65° C., notwithstanding the fact that the water in the jacket is at 13° C.

Curve *a'* shows that the rate of heat-loss in time-units is greater for the first three-tenths of the engine stroke, even with equal mean temperatures. The curve cuts the zero line at a temperature of 165° C., showing that the mean temperature of the wall surface is higher for the inner part than for the whole stroke. This is to be expected for two reasons: the piston end, valves and caps are not water-jacketed, and their surface temperature is doubtless higher than the jacketed part, so that the inner portion presents a larger proportion of hot surface; also the mean temperatures of gases at the inner end are higher than those at the outer end, so that the surfaces must be hotter than those exposed at the outward end of the stroke. This fact explains the smaller heat-loss at the lower temperatures. The crossing of the line *a* by *a'* proves the greater rate of heat-loss at the inner end; this greater heat-loss appears to be due partly to the greater mean density of the gaseous contents at the inner end, and partly to the larger proportion of the cooling surface of the admission port to the whole surface towards the inner end.

Taking curve *b* for whole stroke and hotter cylinder and comparing it with curve *b'* similar relations are apparent, but here the mean temperatures of the wall-surface are much higher— 190° C. for curve *b* (whole stroke), and 400° C. for curve *b'* (three-tenths stroke). The total surface exposed when the piston is full out is approximately 11.2 square feet, and at three-tenths out about 6.5 square feet. Calculating for equal temperature differences, it is found that the heat-flow per square foot per second at the three-tenths end is from 2.5 to 2.8 times that obtained for the whole stroke.

From this follows the necessity of determining the heat-flow separately for each part of the expansion curve investigated; the quantitative law of heat-flow varies with surface exposed and density of working fluid, as well as with temperature. Every part of the stroke will give distinct heat-flow values. For three-tenths stroke, for example, a temperature difference of 700° C. causes a heat-flow of 8537 foot-lbs. per square foot per second, while

for the whole stroke 700° C. difference only gives 3340 foot-lbs. per square foot per second. That is, increase of density and change of configuration are together responsible for the greatly increased rate of heat-loss per unit surface in unit time.

Calculation of the Total Heat given to the Combustible Mixture from the Indicator Diagram only.—If the results given as to apparent specific-heat, temperature-fall, and heat-flow values be correct, then the total heat given to the combustible mixture may be calculated by diagram only. To test this, three diagrams were taken from the engine while it was running at 160 revolutions per minute under a load of 50 brake horse-power. The diagrams are numbered 22 to 24. The heat-flow determinations were made as described, and plotted in work units per whole stroke.

Fig. 10 shows the mean curve. The apparent specific-heat values were calculated for the proper ranges of temperature from the curve, fig. 8. The charge temperature before compression was determined by a method which need not be described here ; it was 95° C.

Three balance-sheets were calculated from the data as follows :—

Card No. 22.

	ft.-lbs.	Per cent.
Heat-flow during explosion and expansion	12,480	15·4
Heat contained in gases at end of expansion	39,800	49·0
Indicated work	28,900	35·6
Total heat	81,180	

i.e., 104 B.T.U.

Card No. 23.

	ft.-lbs.	Per cent.
Heat-flow during explosion and expansion	14,000	17·0
Heat contained in gases at end of expansion	40,500	49·3
Indicated work	27,700	33·7
Total heat	82,200	

i.e., 106 B.T.U.

Card No. 24.

	ft.-lbs.	Per cent.
Heat-flow during explosion and expansion	13,100	16·0
Heat contained in gases at end of expansion	40,600	49·5
Indicated work	28,260	34·5
Total heat	81,960	

i.e., 106 B.T.U.

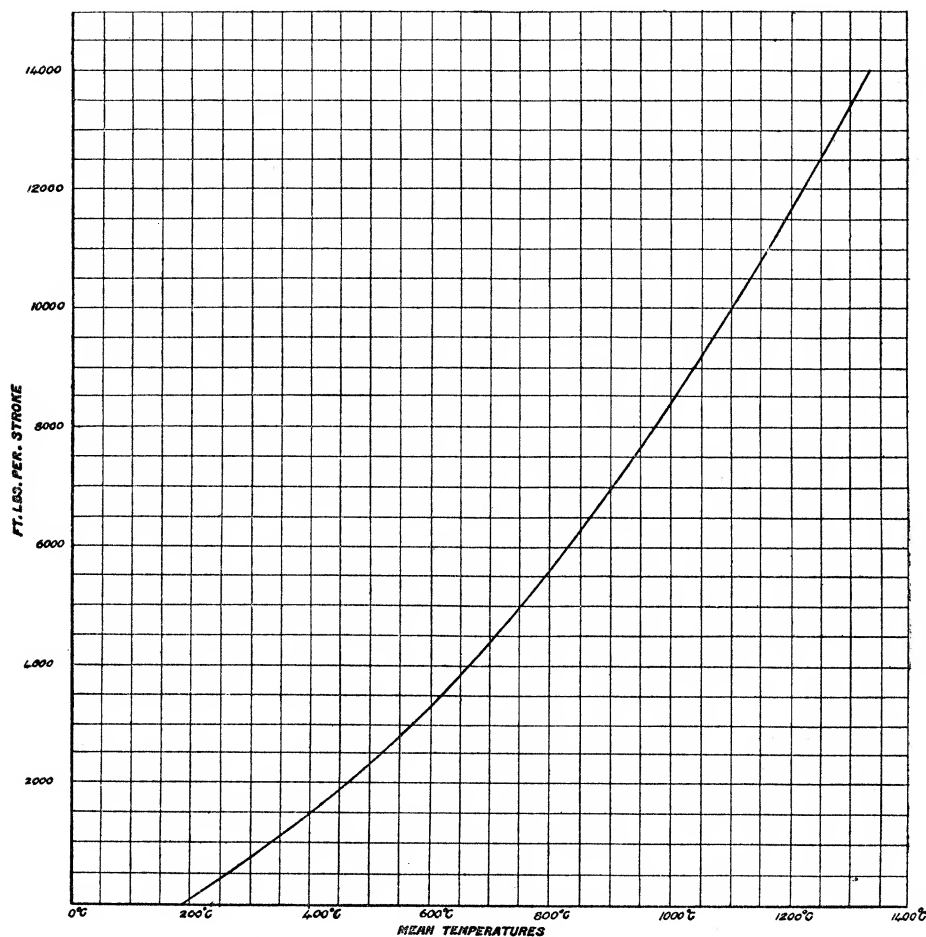


FIG. 10.

These values give the total heat accounted for by the indicator diagram of this particular internal combustion engine, and its distribution in indicated work, necessary exhaust-loss and heat-flow through the cylinder walls.

The diagram informs us that in all 104 to 106 British thermal units have been given to the gases in the cylinder for each power explosion. If this method be correct, then the total heat so found should correspond with that known to be present from the measurement of gas supply. The coal-gas present in the mixture per explosion was 0.183 cubic foot. Its lower heat value was 574 B.T.U per cubic foot.

$$0.183 \times 574 = 105 \text{ B.T.U.}$$

The diagram thus accounts for the 105 B.T.U. known to be present in the form of coal-gas.

Calculations from other indicator diagrams confirm the correspondence of the diagram calculated heat values with those determined from the heat values of the gas known to be present.

These apparent specific-heat and heat-flow values now make it possible for the first time to study the thermodynamic problems of the internal combustion motor from the indicator diagram only, and this the writer believes will materially hasten the development of a complete theory of these motors by making it possible to determine the principal properties of flame in the engine cylinder itself. Many obscure phenomena are capable of investigation by the method.

Earlier Investigations.—Many chemists and physicists have experimented with gaseous explosions, including Hirn, Bunsen, Mallard and Le Chatelier, Berthelot and Vieille, Witz, Dixon, Clerk, Grover, Petavel, and Bairstow and Alexander. All have observed a deficit of pressure for heat of combustion known to be available; many explanations have been offered, as—cooling loss to walls, dissociation of steam and carbon dioxide, increase in specific heat, and combustion at a time rate.

In 1886 the present writer made experiments with coal-gas and hydrogen explosions with air, and he stated that “the author’s experiments prove that the generalisations arrived at by chemists, for the very slow chemical actions investigated by them at low temperatures, hold equally good in the case of rapid chemical combinations occurring at high temperatures producing explosion. In a rich mixture, where the acting gases are but little diluted by neutral gas, the combination is at first exceedingly rapid, but becomes slower as it proceeds, because of the diluting effect of the products. In a poor mixture, when the molecules of the acting gases are widely separated by diluent, the combustion is slow from the first.”

This position is now very generally accepted among investigators in chemical physics, and it is undoubtedly true of rapid as well as slow combinations. When the writer began the present investigation, he believed that these phenomena of slower chemical action furnished a complete explanation of the discord between the theoretical and observed results, and that there was no need to assume any considerable dissociation or variation of specific heat of the products of combustion. These experiments, however, appear to him to indicate real change of specific heat as well as continuation of combustion. The experiments do not exclude dissociation or any other molecular change which by requiring the performance of work would change specific heat. It appears improbable, however, that dissociation should be

material for temperatures so low as 600° C. It is not usual to suppose that either carbon dioxide or steam can be decomposed to any sensible extent at such temperatures.

Mallard and Le Chatelier developed the theory of specific-heat change fully in 1883 from their experiments on explosion in closed vessels, and they give the following formulæ for the mean specific molecular heat at constant volume for carbon dioxide, nitrogen, and oxygen:—

$$\begin{array}{ll} \text{For CO}_2 \dots\dots\dots & C_v = 6.26 + 0.367t \times 10^{-2}. \\ \text{H}_2\text{O} \dots\dots\dots & C_v = 5.61 + 3.28t \times 10^{-3}. \\ \text{N and O} \dots\dots & C_v = 4.8 + 0.006t. \end{array}$$

Dividing respectively by 44, 18, 28, and 32, the molecular weights of carbon dioxide, steam, nitrogen, and oxygen, we get—

$$\begin{array}{ll} \text{For CO}_2 \dots\dots\dots & C_v = 0.1423 + 0.0000834t. \\ \text{H}_2\text{O} \dots\dots\dots & C_v = 0.3116 + 0.000182t. \\ \text{N} \dots\dots\dots & C_v = 0.171 + 0.0000215t. \\ \text{O} \dots\dots\dots & C_v = 0.150 + 0.0000188t. \end{array}$$

These formulæ obviously show that the change of specific heat of the working fluid should be represented by a straight line, and this does not agree with the present experiments. These values, however, agree fairly with the apparent specific heat at 1000° C. and 1500° C.

According to Mallard and Le Chatelier's figures, the mean specific heat of the working fluid used in the present experiments at 1000° C. would be 23.5 foot-lbs. per cubic foot at 0° C. and 760 mm. mercury. The value from Table II of this paper is 24.1 foot-lbs. For 1500° C., Mallard and Le Chatelier works out 25.5 foot-lbs., Table II 25.2 foot-lbs. Mallard and Le Chatelier's observations did not go below 1000° C., as explosions became too slow near that temperature, so that they have estimated specific heats at the lower temperatures by extending the use of the formulæ considerably below the points of observation.

Holborn and Austin have determined the specific heat of carbon dioxide, oxygen, nitrogen and air, at constant pressure, by means of a heating appliance, a thermo-couple, and a calorimeter; but their values are considerably lower than those of Mallard and Le Chatelier, and show a much smaller proportion of increase for CO₂, N, and O, but their numbers appear to be quite consistent with these experiments.

Conclusions.—(1) The apparent specific heat of the working fluid of the internal combustion engine (consisting mainly of a mixture of nitrogen, carbon dioxide, steam and oxygen), when calculated from the first three-

tenths of the engine stroke, undoubtedly increases between the observed temperatures 300° C. and 1500° C., but tends to a limit at the upper temperature.

(2) The apparent change in specific heat is not entirely due to a real change of specific heat, but requires in addition continuing combustion to account for all the facts.

(3) The rate of heat-flow from the working fluid to its enclosing walls for equal temperature differences varies throughout the stroke. Increased heat-flow accompanies increased mean density.

(4) The mean temperature of the inner surface of the enclosing walls varies with the portion of the stroke examined from 190° C. for whole stroke to 400° C. for first three-tenths stroke under working conditions at full load. These mean temperatures, however, are not the highest mean temperatures reached by the walls.

(5) The heat distribution during the operations of the working fluid can be determined with approximate accuracy from the apparent specific-heat values and heat-flow values obtained from the diagram only.

The Richards Casertelli indicator used by the writer for these experiments is one of the best adapted to stand the rough usage of frequent heavy explosions rising above 400 lbs. per square inch; but its indications at the lower pressures are not sufficiently accurate for the purpose of discussing the law of the variation of apparent specific heat throughout the stroke. For this purpose it is desirable to design an indicator of a different type. The writer has examined the leading existing indicators, including the optical instruments of Hospitalier, Carpentier and Petavel, but finds all unsuitable for the delicate work required in order to attain further accuracy in this investigation. The writer has accordingly designed a novel type of mechanical and optical indicator, with which he hopes to obtain diagrams which are sufficiently accurate at the low as well as the high pressures. When these further experiments are made, he trusts that he will be able to distinguish with quantitative accuracy between the phenomena of changing specific heat and continuing combustion.

The writer would point out that the method of investigating specific heat, temperature-fall, and heat-loss here developed is applicable to determinations of the specific heat of gases, heated without combustion. These experiments on the compression of practically a mass of flame show that even at high temperatures the heat-flow to a cylinder is lower on the whole than the rate of addition of heat to the mass of gas by performing work upon it. For example, in many of these experiments one complete compression occupying 0.25 second raises the temperature of the contents of the cylinder from

1000° C. to 1300° C., showing that the rate of heat-flow from the gas, even at a mean temperature of over 1000° C., is considerably less than the rate at which heat can be added to the gas by work performed. From this indication it is evident that a simple gas, such as nitrogen, oxygen, or a compound such as carbonic acid, could be heated by compression alone, in a suitable apparatus, to at least 1500° C. It only requires a sufficiently powerful mechanical apparatus to stand the high pressure of about $1\frac{1}{2}$ tons per square inch to get any desired temperatures. Such determinations will be entirely free from doubt due to possible combustion. The method described requires some modification, owing to the fact that where all the heat is added by compression, at one part of the stroke the gas would be absorbing heat, and at another part giving it out.

My thanks are due to my assistant, Mr. W. Grylls Adams, M.A., for his very effective aid in the laborious work of measuring the diagrams and making the numerical calculations. I have also had much pleasure in discussing with him the somewhat numerous points of difficulty which have arisen in the course of the investigations.

APPENDIX.—Received March 24, 1906.

Mean Temperature.—In the foregoing mean temperature during any expansion or compression stroke or part of a stroke is taken in relation to time, the obliquity of the connecting rod being neglected and the motion of the piston being taken as simple harmonic motion. The error introduced by this assumption is negligible within the accuracy of the experiments.

Division of Heat-Loss between Expansion and Compression Lines.—It will be noticed that the temperature-fall due to heat-loss is divided between compression and expansion lines by drawing a curve whose abscissæ represent mean temperatures, and whose ordinates represent the temperature-fall, and taking the temperature-fall on any expansion line from this curve at the mean temperature of that expansion line.

This involves the assumption that heat-loss would be the same on an expansion line, and on a compression line for the same part of the stroke if the mean temperatures of the two lines were the same.

In considering the whole strokes, the temperature-fall due to heat-loss on an expansion line can be obtained by considering the expansion line with the compression line above it, and also with the compression line below it. This has been done, and it is found that the value thus obtained for the line BC (fig. 2) is the same within the error of experiment, whether it be arrived at by considering the pair of lines AB, BC, or the pair of lines BC, CD, and similar results are obtained for the other lines. This shows that the

temperature-fall due to heat-loss on pairs of lines starting from the lower end of the diagram, can be taken from the temperature-fall curve obtained by considering the pairs of lines starting from the upper end, and hence the value for an expansion line or compression line can also be taken from the curve.

In the consideration of the upper end of the stroke, the case is somewhat more difficult, as the time periods dealt with are not continuous; there will be a difference between compression and expansion strokes, in that on a compression stroke at the upper end of the diagram the gases in contact with the cylinder walls have during the immediately preceding part of the stroke been at a lower temperature, while on the expansion stroke they have been at a higher temperature. On the upper three-tenths stroke therefore the cylinder walls will be at a slightly lower temperature at the beginning of the part of the compression stroke considered than their temperature at the beginning of the part of the expansion stroke considered. The difference of temperature will not be great, and the error introduced by neglecting the difference is a very small one. This error also produces very little effect on the apparent specific-heat value; an error of 10 per cent. in dividing the temperature-fall due to heat-loss between the compression and expansion lines would not produce more than 3 per cent. error in the specific-heat value.

Errors of Reading, Indicator, etc.—In the reduction to normal pressure and temperature no account has been taken of the change of volume due to combustion. This change is small and only affects absolute values, and does not appreciably interfere with the deductions based on comparison of the various figures obtained.

In calculating from the upper three-tenths stroke, an error of $1/200$ -inch on the indicator card, and of $1/100$ -inch on the enlarged photograph, would introduce an error of 3 per cent. on the specific-heat value obtained on the first expansion line, and an increasing error on successive expansion lines amounting to 5 per cent. on the fourth expansion line.

In calculating from the whole stroke an error of $1/200$ -inch on the indicator card, and $1/100$ -inch on the enlarged photograph would introduce an error of 4 per cent. in the specific heat obtained from the first expansion line.

In order to obtain the comparative results given from different parts of the stroke by errors of indicator, etc., it would be necessary to make an error amounting to about $1/50$ -inch on the indicator cards and $1/25$ -inch on the photographs.

There is nothing on the diagrams to suggest such an error as this, and the results are not of the kind that would be produced by indicator slack.

or friction. This can be shown by calculating the specific heat on the same expansion line, taking the heat-loss correction from the next upper and next lower compression lines respectively. It is found that the results are practically the same in the two cases.

The effect of friction and slack is to keep the expansion lines uniformly higher than they should be, while the compression lines are kept lower than they should be.

The result of this is that a temperature-fall measured on an expansion line will be too small, as the same height measured vertically will be equivalent to a greater temperature difference at the lower parts of the diagram; and similarly a temperature-rise measured on a compression line will be too great. The result as regards the specific-heat value found from the upper three-tenths stroke is that frictional error on the expansion line is to a certain extent if not wholly balanced by frictional error on the compression line. This arises in the following manner:—

The error on the expansion line causes the gross temperature-fall on expansion to be too small, but to get the temperature-fall which is equivalent to the work under the expansion line we subtract from the gross temperature-fall a temperature-fall due to cooling, the determining part of which is the temperature difference measured between the compression and expansion lines on the ordinate at the three-tenths stroke. This temperature difference is thus taken too small, and approximately too small by the same amount as the gross temperature-fall is too small.

In calculating the specific heat on a given expansion line a different effect is produced by friction, according to the compression line from which the correction is made for cooling. If an expansion line is considered in connection with the compression line immediately below it, friction causes these two lines to be too far apart instead of too near together. The temperature-fall measured on the expansion line is, as before, too small, but the temperature-fall due to cooling is in this case too great, and therefore the friction will produce an accumulated effect.

The fact that the value obtained for specific heat for the whole expansion line is the same whether that expansion line is considered together with the compression line above it, or with the compression line below it, therefore seems to show that friction and indicator-slack could not be the cause of the results obtained.
